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On spectra of q -deformed operators

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1.

The formal algebraic relation $xx^* = qx^*x$ ($q > 0$, $q \neq 1$) appears in several different situations related to the theory of quantum groups. This leads us to the study of an operator obeying this relation in a Hilbert space. Let q be a positive real number with $q \neq 1$. Let T be a closed densely defined operator in \mathcal{H} . If T satisfies

$$TT^* = qT^*T,$$

then T is called a *deformed normal operator* with deformation parameter q . Let T be a closed densely defined operator in \mathcal{H} with polar decomposition $T = U|T|$. If T satisfies the relation

$$U|T| = \sqrt{q}|T|U,$$

then T is called a *deformed quasinormal operator* with deformation parameter q . For a deformed normal (resp. deformed quasinormal) operator T with deformation parameter q , we will simply say T is *q -normal*. (resp. *q -quasinormal*)

If T is q -normal then T is q -quasinormal. A closed densely defined operator T is q -normal if and only if

$$\mathcal{D}(T) = \mathcal{D}(T^*) \quad \text{and} \quad \|T^*\eta\| = \sqrt{q}\|T\eta\| \quad (\eta \in \mathcal{D}(T)).$$

A densely defined operator T is called a *q -hyponormal operator* (or a *deformed hyponormal operator* with deformation parameter q) if it satisfies

$$\mathcal{D}(T) \subseteq \mathcal{D}(T^*) \quad \text{and} \quad \|T^*\eta\| \leq \sqrt{q}\|T\eta\|$$

for all $\eta \in \mathcal{D}(T)$. If T is q -quasinormal, then T is q -deformed hyponormal.

Let T be a q -deformed hyponormal operator in \mathcal{H} . Then there exists uniquely a contraction K_T such that

$$T^* \supseteq \sqrt{q}K_T T \quad \text{and} \quad \ker K_T \supseteq \ker T^*.$$

K_T is called the attached contraction to T . If, in addition, T is closed and $T = U|T|$ is the polar decomposition, then T is q -quasinormal if and only if $K_T = (U^*)^2$.

2. Unbounded weighted shifts

Let S_b be a closed densely defined operator in a separable Hilbert space \mathcal{H} . If there are an orthonormal basis $\{e_n\}$ ($n \in \mathbb{Z}$) and a sequence $\{w_n\}$ ($w_n \neq 0, n \in \mathbb{Z}$) of complex numbers such that

$$\mathcal{D}(S_b) = \left\{ \sum_{-\infty}^{\infty} \alpha_n e_n \in \mathcal{H} : \sum_{-\infty}^{\infty} |\alpha_n|^2 |w_n|^2 < \infty \right\}$$

and

$$S_b e_n = w_n e_{n+1}$$

for all $n \in \mathbb{Z}$, then S_b is called a *bilateral (injective) weighted shift* with weight sequence $\{w_n\}$ (with respect to $\{e_n\}$). A unilateral weighted shift S_u is defined analogously.

Proposition. The following statements hold:

1. A unilateral weighted shift S_u in \mathcal{H} with weights $\{w_n\}$ is q -quasinormal if and only if

$$|w_n| = \left(\frac{1}{\sqrt{q}} \right)^n |w_0|$$

for all $n \geq 0$. In particular, a unilateral weighted shift cannot be q -normal.

2. A bilateral weighted shift S_b in \mathcal{H} with weights $\{w_n\}$ is q -normal if and only if the above equation is valid for all $n \in \mathbb{Z}$
3. A weighted shift S_u (resp. S_b) is q -hyponormal if and only if

$$|w_{n+1}| \geq \frac{1}{\sqrt{q}} |w_n|$$

for all $n \geq 0$ (resp. $n \in \mathbb{Z}$).

The spectrum of a q -normal weighted shift S_b :

	σ_p	σ_c	σ_r	σ
$S_b (0 < q < 1)$	\emptyset	$\{0\}$	$\mathbb{C} \setminus \{0\}$	\mathbb{C}
$S_b (q > 1)$	$\mathbb{C} \setminus \{0\}$	$\{0\}$	\emptyset	\mathbb{C}

The spectrum of a q -quasinormal weighted shift S_u :

	σ_p	σ_c	σ_r	σ
$S_u (0 < q < 1)$	\emptyset	\emptyset	\mathbb{C}	\mathbb{C}
$S_u (q > 1)$	\emptyset	\emptyset	$\{0\}$	$\{0\}$

3. Spectra of a q -hyponormal operator

Theorem. Let T_1 and T_2 be q -hyponormal operators in a Hilbert space \mathcal{H} . Then $T_1 \oplus T_2$ is also q -hyponormal in $\mathcal{H} \oplus \mathcal{H}$ and

$$K_{T_1 \oplus T_2} = K_{T_1} \oplus K_{T_2}.$$

Moreover, $T_1 \oplus T_2$ is q -normal (resp. q -quasinormal) if and only if both T_1 and T_2 are q -normal (resp. q -quasinormal).

In case that $0 < q < 1$, a non-trivial q -hyponormal operator is always unbounded and the planar Lebesgue measure of its spectrum is positive.

Let $q > 1$. Then, there are various kinds of q -deformed operators, bounded or unbounded:

- A q -quasinormal unilateral weighted shift is always bounded.
- There exist q -quasinormal operators which are unbounded; they are q -normal ones.
- Using Theorem, one can construct an unbounded q -quasinormal operator which is not q -normal. (For this take T_1 to be any q -normal operator (which must be unbounded) and T_2 to be a bounded q -quasinormal unilateral weighted shift.)
- There exists a q -hyponormal operator which has empty spectrum, which is given in the following section; this is in contrast to the fact that every closed densely defined hyponormal operator ($q = 1$) has to have non-empty spectrum.

4. A q -deformed operator with empty spectrum

Let T be a closed densely defined operator in a Hilbert space \mathcal{H} . Recall that the resolvent set $\rho(T)$ of T is defined as the set of all $\lambda \in \mathbb{C}$ for which $\ker(\lambda - T) = \{0\}$, $\mathcal{R}(\lambda - T) = \mathcal{H}$ and the inverse $(\lambda - T)^{-1}$ is bounded on \mathcal{H} . Especially,

$$0 \in \rho(T)$$

if and only if there is a bounded operator S on \mathcal{H} such that

$$ST \subseteq 1 \quad \text{and} \quad TS = 1.$$

Lemma. Let T be a closed densely defined operator in \mathcal{H} . Suppose that

$$\rho(T) \ni 0.$$

If $\sigma(T^{-1}) = \{0\}$, then

$$\sigma(T) = \emptyset.$$

Let $q > 1$. Let \mathcal{H} be a separable Hilbert space with orthonormal basis $\{e_n\}_{n \in \mathbb{Z}}$. Take numbers r and ℓ such that

$$\ell > 1 > r \geq \frac{1}{\sqrt{q}}.$$

Put

$$w_n = \begin{cases} r^n & \text{if } n \geq 0, \\ \ell^n & \text{if } n \leq -1. \end{cases}$$

Let us consider the weighted shift S_0 with the weight sequence $\{w_n\}$. Then, clearly S_0 is bounded with $\mathcal{D}(S_0) = \mathcal{H}$. Since the sequence $\{w_n\}$ tends to zero as $|n| \rightarrow \infty$, S_0 is compact and so $\sigma(S_0)$ is countable. On the other hand,

$$\sigma(S_0) = c\sigma(S_0)$$

for all $c \in \mathbb{C}$ with $|c| = 1$. It follows that $\sigma(S_0) = \{0\}$.

Since $\ker(S_0) = \ker(S_0^*) = \{0\}$, S_0 is injective and has dense range. This means that the inverse S_0^{-1} is closed and densely defined. Hence, it follows from Lemma that S_0^{-1} has empty spectrum. On the other hand, we have

$$\frac{w_{n+1}}{w_n} = r \geq \frac{1}{\sqrt{q}} \quad \text{for } n \geq 0,$$

and

$$\frac{w_{n+1}}{w_n} = \ell > 1 > \frac{1}{\sqrt{q}} \quad \text{for } n \leq -1.$$

These inequalities imply that S_0 is q -hyponormal. Therefore, S_0^{-1} is also q -hyponormal. Thus we have:

Theorem. Let $q > 1$. Then, there exists a q -hyponormal operator with empty spectrum.

5. Order relations for q -deformed operators

Let us recall some inequalities by Kato and Rellich ([1] and [5]) :

$$S \ll T \text{ means } \mathcal{D}(T) \subseteq \mathcal{D}(S), \text{ and } \|S\eta\| \leq \|T\eta\| \text{ for } \eta \in \mathcal{D}(T)$$

and

$$S \preceq T \text{ means } \mathcal{D}(T^{\frac{1}{2}}) \subseteq \mathcal{D}(S^{\frac{1}{2}}) \text{ and } \|S^{\frac{1}{2}}\eta\| \leq \|T^{\frac{1}{2}}\eta\| \text{ for } \eta \in \mathcal{D}(T^{\frac{1}{2}})$$

provided S and T are selfadjoint and nonnegative.

Definition. Let S and T be symmetric (densely defined) operators in \mathcal{H} . If

$$\mathcal{D}(T) \subseteq \mathcal{D}(S) \quad \text{and} \quad \langle S\eta, \eta \rangle \leq \langle T\eta, \eta \rangle$$

for all $\eta \in \mathcal{D}(T)$, then we write

$$S \leq T.$$

Theorem. Let T be a closed densely defined operator in \mathcal{H} . We consider the following statements:

- (1) T is q -hyponormal.
- (2) T satisfies the condition $|T^*| \ll \sqrt{q}|T|$.
- (3) T satisfies the condition $|T^*| \leq \sqrt{q}|T|$.
- (4) T satisfies the condition $|T^*| \preceq \sqrt{q}|T|$.

Then, $(1) \iff (2) \implies (3) \implies (4)$.

Especially, if T is a weighted shift, unilateral or bilateral, then all these statements are equivalent.

Theorem. If a closed densely defined operator T in \mathcal{H} satisfies condition

$$TT^* \leq q T^*T,$$

then T is q -hyponormal.

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